# Gamma-ray bursts: the tip of the iceberg?

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**Abstract.** The spin-energy $E_{rot}$ of a Kerr black hole surrounded by a torus may power emissions in multiple windows. The recently determined true GRB-energy $E_\gamma = 3 - 5 \times 10^{50}$erg indicates a minor fraction $E_j/E_{rot} \simeq$ 0.1% in baryon poor output, here considered as jets along open magnetic flux-tubes from the horizon to infinity. A major fraction $E_{gw}/E_{rot} \simeq 5\%$ is expected in gravitational radiation from the torus. A LIGO/VIRGO detection of $\alpha = 2\pi \int f dE_{gw}$ in excess of the neutron star limit $\alpha^* \simeq 0.005$ promises a calorimetric test for Kerr black holes. We expect a sample of LIGO/VIRGO detections to obey the distribution of redshift corrected GRB-durations.

## INTRODUCTION

Black hole-torus systems may represent high-energy astrophysical transient sources. They feature the prospect of multi-window emissions powered by the spin energy $E_{rot}$ of a Kerr black hole. This could take the form of outflows along the axis of rotation accompanied by emissions from the torus in various channels: gravitational radiation, Poynting flux-dominated and baryonic winds and, when sufficiently hot, neutrino emissions. Ultimately, these systems may provide definitive tests for Kerr black holes as objects in Nature – the most compact energy reservoirs in angular momentum.

Rotating black holes where discovered by Kerr as exact solutions to general relativity [1]. The specific angular momentum of their radiation is at least twice that of the black hole, which suggests that Kerr black holes may be luminous under appropriate conditions. Identifying Kerr black holes will require observational evidence for its defining properties (see [34]): a compact horizon surface in common with non-rotating Schwarzschild black holes; frame-dragging of space-time is described by an angular velocity $-\beta$ of zero angular momentum observers; a compact energy reservoir of energy $E_{rot} = 2M \sin^2(\lambda/4)$, where $a/M = \sin\lambda$ denotes the ratio of specific angular momentum $a$ to the black hole mass $M$. In an extreme Kerr black hole, about half of the rotational energy corresponds to the top ten percent of the angular velocity $\Omega_H = \tan(\lambda/2)/2M$.

Black hole-torus systems harboring Kerr black holes are leading candidates as the inner engine of gamma-ray bursts (see [9] for a review). GRBs are characteristically non-thermal in the range of a few hundred keV with a bi-modal distribution in durations of short bursts around 0.3s and long bursts around 30s [2]. Black hole plus disk or torus systems may represent failed-supernovae [10] hypernovae [11] or black hole-neutron star coalescence [12], where the former is intimately connected to star forming regions [11, 13]. With GRBs remnants potentially found in Soft X-ray transients [14] GRO J1655-40 [15] and V4641Sgr [16], the putative black hole assumes the observed mass-range $3 - 14M_\odot$ (Fig. 1). We recently identified long/short bursts with rapidly/slowly spinning black holes in a state of suspended-/hyperaccretion [17]. A mean de-redshifted duration on the order of tens of seconds corresponds to the life-time of rapid spin in suspended accretion in the presence of superstrong magnetic fields.

Here, we focus on baryon poor jets along the axis of rotation along with gravitational radiation from the torus. As proposed input to GRBs, the former will represent a minor fraction of $E_{rot}$ as inferred from the recently determined true GRB-energies [18, 19]. The latter is expected to be a major fraction of the output which could be representative for $E_{rot}$. We thus expect LIGO/VIRGO to detect a distribution of durations in gravitational waves which corresponds to the presently observed redshift-corrected distribution of GRB-durations.

## MULTI-WINDOW EMISSIONS

A Kerr black hole is expected to be luminous over *all* horizon angles, in response to a generally uniform magnetic flux. Thus, we expect emissions along its axis of rotation as well as into the surrounding matter. A detailed analysis is based on the topology of the magnetic field, partly by equivalence to pulsar magnetospheres and the formation of open flux-tubes.
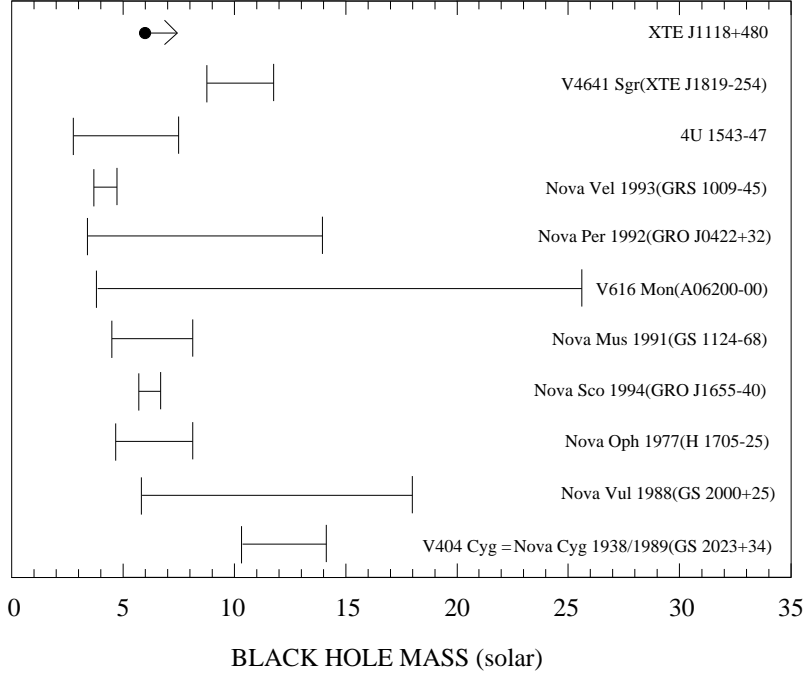
**FIGURE 1.** Shown is the distribution of black hole masses in X-ray novae. The top four are XTE J118+408 [20] V4641 Sgr [16], 4U 1543-47 [21] and Nova Vel 1993 [22]; the lower seven are from [23]. This mass distribution manisfests a certain diversity in black hole masses of about $3 - 14 M_\odot$. [Reprinted from van Putten, *Physics Reports*, 345 ©2001 Elsevier B.V.]

In its lowest energy state, a rotating black hole surrounded by a torus magnetosphere develops an equilibrium magnetic moment [9]

$$\mu_H \simeq aBJ_H, \qquad (1)$$

where $B$ denotes the mean of the poloidal magnetic field in the surrounding torus magnetosphere. It corresponds to the Wald equilibrium charge [27] consistent with the no-hair theorem [28, 9]. It carries over to a largely force-free magnetosphere around a black hole [29] and, in scaling, is analogous to the equilibrium charge on a neutron star [30]. The black hole hereby maintains essentially a maximal and uniform horizon flux at arbitrary rotation rates.

## Baryon-poor jets

A rapidly rotating black hole may support an open flux-tube supported by Eqn.(1). These are endowed with slip/slip- and ingoing/outgoing-boundary conditions on the horizon/infinity. The charge-density about the axis of rotation of the black hole satisfies $\rho = -(\Omega + \beta)B/2\pi$ (see [9] for references), where $\Omega$ denotes the angular velocity of the open flux-tube; a sign-change from positive in a lower section attached to the black hole to negative in the semi-infinite section above occurs at some height

above the black hole when $0 < \Omega < \Omega_H$. This permits a continuous current along the open flux-tube from infinity into the hole, with outflow to infinity and inflow into the black hole. Open magnetic flux-tubes are a remarkable natural phenomenon, perhaps most dramatically demonstrated by solar activity. Magnetic mediated outflows in general, therefore, require the creation of open magnetic flux-tubes which formally extend to infinity. Open magnetic flux-tubes may be created from a torus magnetosphere around a black hole, by change in topology [9]. This change in topology represents transient fast magnetosonic wave, which might be excited as a nonlinear feature to strong Alfvén waves or by superradiance within the torus magnetosphere. It produces a coaxial structure of two flux-tubes, an inner tube supported by the equilibrium magnetic moment of the black hole and an outer tube supported by the torus. The flux in the inner/outer tube is $\pm 2\pi A_\phi$ in terms of the vector potential $A_\phi$. The outer flux-tube endowed with no-slip/slip boundary conditions on the surface of the torus/infinity.

The inner flux-tube forms an powerful artery for the spin-energy of the black hole. In asymptotically charge-separation equilibrium, it assumes an angular velocity $\Omega_+$ on the horizon and $\Omega_-$ at larger distances by the slip-slip boundary conditions. These lower and upper sections are separated by differential rotation. For a net flux $2\pi A_\phi$, the ingoing boundary conditions produce a current $I_+ = (\Omega_H - \Omega_+)A_\phi$ in the small angle approxima-

tion [31, 9]; likewise, the current at infinity is $I_- = \Omega_- A_\phi$ for ultrarelativistic winds [9]. This leaves a Faraday-induced potential $V = (\Omega_+ - \Omega_-)A_\phi$ along the differentially rotating inner tube. Global current closure is over the outer flux-tube, which corotates with the angular velocity $\Omega_T$ of the torus by its no-slip boundary conditions. By current continuity, differential rotation hereby creates a baryon-poor jet with luminosity [9]

$$L_j = \frac{1}{2}\Omega_T(\Omega_H - 2\Omega_T)A_\phi^2. \qquad (2)$$

These low-$\sigma$ outflows may represent the baryon-poor input to cosmological gamma-ray bursts (GRBs). When the low-$\sigma$ outflow is hidden from view by an intervening medium, the observed spectrum will be different from black body radiation. The observed spectrum - but less so the characteristic energies – depends on the subsequent evolution of this medium and its interaction with the interstellar medium. In particular, the non-thermal GRB emissions may hereby be the testimonial to a hypernova progenior wind, associated with its rapid rotation and consistent with the recently discovered iron line emissions [32]. This introduces shocks and synchrotron radiation. The observed emissions, therefore, should be non-thermal with approximately similar characteristic energies as emitted from the gap. The detailed structure of the emissions further depends on the interaction of this accelerated wind mass with the interstellar medium [4].

The recenlty inferred true GBR-energies of $3 - 5 \times 10^{50}$erg [18, 19] imply $E_j/E_{rot} \simeq 0.01\%/\varepsilon$ in baryon poor outflows. Here $\varepsilon \simeq 0.15\%$ denotes the radiation efficiency, assuming $E_{rot} \simeq M/3$ with $M = 7M_\odot$. As a specific application of (2), this indicates an open flux-tube with half-opening angle $\theta_H \simeq 35^o$ [33]. The half-opening angles on the celestial sphere will satisfy $\theta_j \leq \theta_H$. The duration of the burst and the observed half-opening angles $\theta_j$ may be uncorrelated, upon collimation by external parameters such as hydrostatic static pressure in a GBR-precursor winds or the interstellar medium, or positively correlated, upon collimation by winds [24] coming off the torus.

## Gravitational radiation

A surrounding torus receives energy and angular momentum by equivalence in poloidal topology to pulsar magnetospheres: the inner face of a torus around a black hole receives energy and angular momentum, as does a pulsar when infinity wraps around it. The outer face looses angular momentum and energy to infinity, as does a pulsar in flat space-time. These equivalences becomes apparent when working in a frame of references fixed to the horizon of the black hole and, respectively, infinity

(Mach's principle). When the black hole spins rapidly, it develops a state of suspended accretion for the duration of rapid spin of the black hole. The high incidence of the black hole-luminosity onto the inner face indicates that the emissions from the torus may be luminous. We thus find an output

$$E_{gw} = 1 - 2\%M \qquad (3)$$

in gravitational radiation – about two orders of magnitude higher than the inferred true GRB-energies.

The major fraction $E_{gw}/E_{rot} \simeq 5\%$ emitted at twice the Keplerian frequency, i.e., $f = 1 - 2$kHz, promises black hole-torus systems to be viable sources for the upcoming broadband gravitational wave observatories LIGO [25] and VIRGO [26]. Thus, black hole-torus systems may have a compactness parameter [34]

$$\alpha = 2\pi \int_0^{E_{gw}} f dE > \alpha^* \simeq 0.005 \qquad (4)$$

in excess of the limit for rapidly spinning neutron stars. This provides for the first time a *calorimetric* compactness test for Kerr black holes. The proposed association to GRBs predicts that a future sample of LIGO/VIRGO detections will satisfy a distribution of durations which obeys the distribution of redshift corrected GRB-durations $T/(1+z)$ (Fig. 2). The displayed spread in $T/(1+z)$ is consistent with the narrow mass range of $3 - 14M_\odot$ in SXTs. Indeed, we expect a positive correlation between $T/(1+z) \propto M^2$ and $E_{gw} \propto M$ (as well as $E_j$ and $E_\gamma$) in view of $E_{rot} \propto M$ and a black hole-to-torus coupling $\propto M^{-1}$ for a universal ratio of poloidal magnetic field energy-to-kinetic energy in the torus [35].

## SUMMARY

We have described a prospect for multi-window emissions from Kerr black holes powered by its rotational energy. Surrounded by a torus, a Kerr black hole is luminous over *all* horizon angles in its lowest energy state. These systems are long-lived in a state of suspended accretion, which operates by equivalence in poloidal topology to pulsar magnetospheres. Quite generally, the powerful competing torques acting on the torus introduce turbulent shear flow, which may stimulate the formation of a quadrupole moment in its mass distribution. We expect a minor fraction in baryon-poor jets from a differentially rotating tube along the axis of rotation and a major fraction in gravitational radiation from the torus. (Further output is expected in torus winds and, when sufficiently hot, neutrino emissions.) These black hole-torus systems are predicted to be powerful LIGO/VIRGO-sources of gravitational radiation, permitting for the first time a calorimetric compactness test for Kerr black holes. A
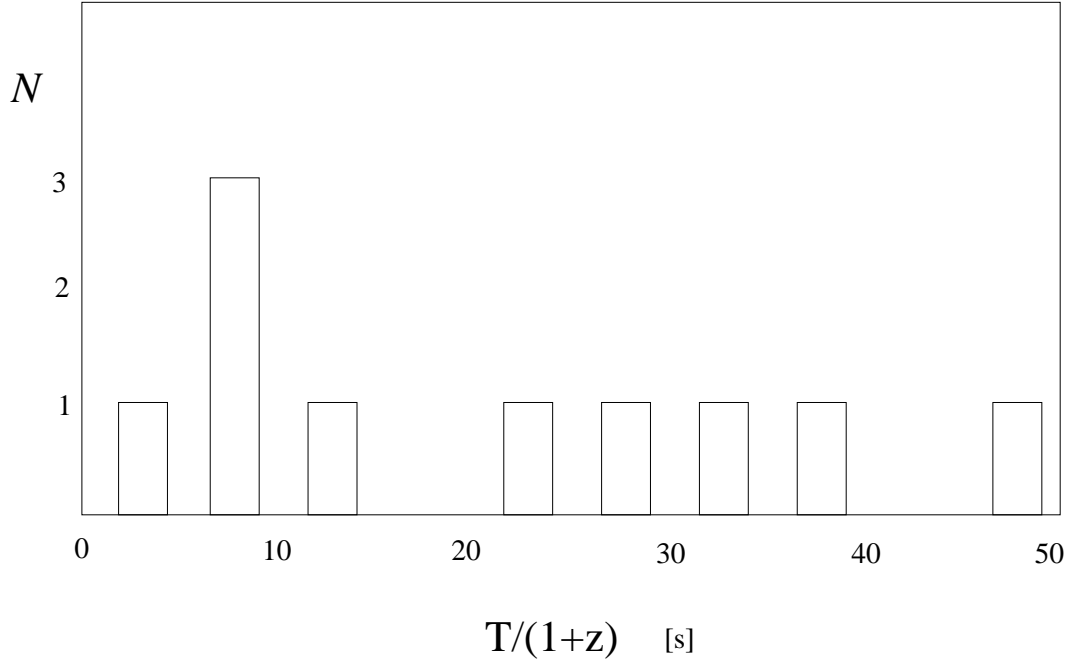
**FIGURE 2.** Shown is the distribution of redshift corrected durations, obtained from 10 GRBs with individually determined redshifts from their afterglow emissions (GRB000926,GRB000418,GRB000301c,GRB990510,GRB990123,GRB980613, GRB980425,GRB971214,GRB970508,GRB970228). This distribution represents the life-time of the inner engine. In the black hole-torus model, the proposed gravitational radiation from the torus is simultaneous with the baryon-poor output powering the GRB. LIGO/VIRGO detections of these emissions (from cosmologically nearby sources) are expected to obey a similar distribution.

sample of LIGO/VIRGO detections is predicted to obey the distribution of redshift corrected GRB-durations.

## ACKNOWLEDGMENTS

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